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PHOSPHORUS REMOVAL FROM EFFLUENTS IN ALUMINA COLUMNS

Lloyd L. Ames, Jr., and Robert B. Dean

Sawyer (1) has stated that phosphorus may represent the major uncontrolled pollutant now released to the environment in wastewater. According to Stephan (2), the average soluble phosphorus content of municipal secondary effluent is 8.3 mg P/l. Other anions include Cl^- at 130 mg/l, N at 3.3 mg/l, HCO_3^- at 300 mg/l, and SO_4^{-2} at 100 mg/l.

Previous Studies

Combined chemical-biological wastewater treatment and phosphorus-removal systems are now under study and development (3) (4) (5) (6) (7) (8), as are tertiary chemical-physical removal processes (9) (10) (11) (12). However, the above treatment systems operate most economically as large-scale processes. A simple, economical phosphorus-removal process would be desirable for the smaller 1- to 10-mgd (3,785- to 37,850-cu m/day) trickling filter wastewater treatment plants. A phosphorus polishing process may also be required for the larger, combined treatment plants.

Few, if any, of the suggested or proven chemical-physical processes for phosphorus removal have contemplated the use of ion exchange. There is little economic incentive for using a conventional ion-exchange process for phosphorus removal. Use of an organic resin requires removal of nearly all the other anions in addition to phosphorus, resulting in 1 l of resin treating 80 l or less of average secondary wastewater effluent containing approximately 600 mg/l of assorted anions.

In addition to low efficiency of phosphorus removal, the problems of disposal of large regenerant waste volumes and use of relatively large process equipment are encountered with nonselective processes. Plainly, a more phosphorus-selective adsorbent is required if adsorption removal processes are to be economically attractive. Such a potentially economical process results from using alumina in adsorption columns. Anion-exchange reactions on aluminas are well known. For example, Schwab (13) stated that the adsorption of ions, both cations and anions, on alumina takes place by displacement of ions of equal sign contained in the alumina surface. Shuvaeva and Gapon (14) also interpreted alumina chromatographic separations to mean that ion exchange is the primary mechanism involved in ion removal. They also showed that secondary adsorption occurs during removal of multivalent ions. Shibata (15) gives a cation-adsorption series on alumina, in decreasing order of preference, as Fe^{+3}, Hg^{+2}, Pb^{+2}, Cu^{+2}, Zn^{+2}, Ca^{+2}, Ni^{+2}, Fe^{+2}, and Mn^{+2}, approximately the adsorption order for a normal hydrated ion series. Kubli (16) found the anion alumina adsorption series, in order of decreasing preference, to be OH^-, PO_4^{-3}, $C_2O_4^{-2}$, F^-, SO_3^{-2}, CrO_4^{-2}, NO_2^-, Cl^-, NO_3^-, MnO_4^-, and SO_4^{-2}.

Yee (17) first made use of the chromatographic properties of high-surface-area alumina for the selective re-

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moval of phosphorus from wastewater. He reported that a downflow, 2-ml alumina column could process about 1,600 column volumes of a synthetic waste containing 25 mg PO_4/l as orthophosphates to 1 percent breakthrough. Upflow tests were run on larger 200-ml columns using low-level radioactive process wastewater containing about 1 to 3 mg PO_4/l and suspended solids. Yee estimated that about 20,000 column volumes of the above waste could be processed to 1 percent phosphate breakthrough in the effluent. Higher waste throughputs were reported for forms of phosphorus other than orthophosphates. However, since biological treatment hydrolyzes 90 percent or more of the phosphorus, orthophosphates will predominate (18).

In Yee's work, the adsorbed phosphorus was stripped from the alumina column with 1 *M* NaOH and the column reacidified with 1 *M* HNO_3 for a total of 12 to 16 column volumes of regenerant waste produced. Alumina losses during regeneration were given as 5 to 35 percent, depending on the type of alumina used. No continuous-cycling data were given for phosphorus removal on alumina columns. Yee estimated that phosphorus removal from wastewaters on alumina columns would be $39.00/mil gal ($0.01/cu m) in the case of a 14-mg PO_4/l influent to $64.00/mil gal ($0.017/cu m) for a 23-mg PO_4/l influent. Eight percent per cycle alumina losses were assumed in the above cost estimates.

TABLE I.—Synthetic Secondary Wastewater Effluent*

Constituent	Concentration (mg/l)
Na^+	130
K^+	25
NH_4^+	20
Ca^{+2}	60
Mg^{+2}	25
Cl^-	112
HCO_3^-	300
SO_4^{-2}	50
P	3.5–10.3

* pH = 7.4.

Neufeld and Thodos (19) recently published the results of a laboratory study of phosphorus removal with alumina and several synthetic aqueous influents. No phosphorus-removal data were generated using actual wastewater effluents. These authors also assumed that an acidic regeneration step was necessary to prepare the alumina column for reloading. Phosphorus removal on alumina was reported as a complex ion exchange-recrystallization process.

Laboratory research at Battelle-Northwest has extended the work of the above authors and applied these results to a phosphorus-removal process using a municipal secondary trickling filter effluent.

Laboratory Studies

Small Alumina Columns

A synthetic secondary wastewater effluent was used in the small column studies. The composition of the synthetic, to be referred to as SSE, is given in Table I. The SSE was used as a standard influent and was compositionally altered to determine the effects of the changes on phosphorus removal by alumina.

Small, 1.1-cm diam by 8.0-cm high columns were used with the above SSE to determine alumina phosphorus removal. The SSE was pumped through the column at a predetermined rate. Column effluent was sampled at intervals and the phosphorus content of the sample determined by the standard ammonium molybdate-aminodisulfonic acid method. The phosphorus-removal values were plotted as C/C_o vs. volume of throughput, where C equals the phosphorus concentration in the effluent and C_o is the phosphorus concentration in the influent.

Ion Exchange

Several investigators of alumina adsorption phenomena have considered

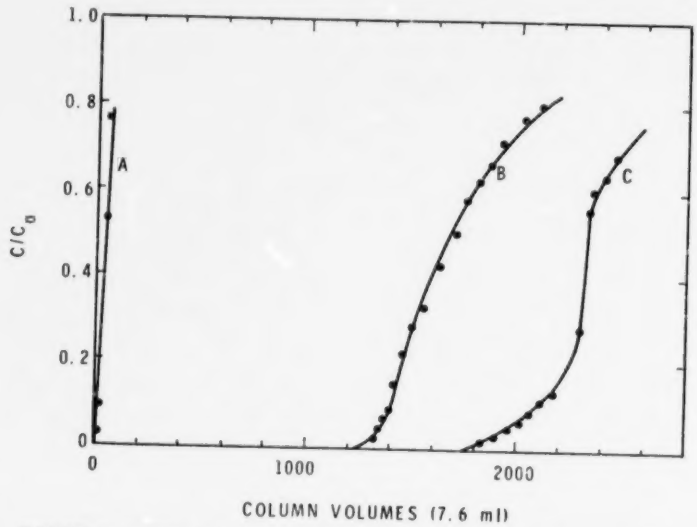

FIGURE 1.—Phosphorus loading of aluminas of different surface areas. Column materials: A—boehmite, 22 sq m/g; B—boehmite, 200 sq m/g; C—gel, 292 sq m/g. Influent: SSE with 7.0 mg P/l; flow rate: 30 column volumes/hr; temperature: 23°C.

that the adsorption is essentially a highly selective ion-exchange process. With that assumption, increasing the surface area of the alumina should increase the phosphorus-adsorption capacity of the alumina. Three different columns containing aluminas of known surface area were compared with respect to their phosphorus capacities, with the results shown in Figure 1. A simple and direct relationship between alumina surface area and phosphorus capacity was indicated. Surface area effects probably overshadowed any effects due to differences in the crystalline structure of the alumina. The boehmite columns, for example, treated less SSE than the nonerystalline alumina, and also were less in surface area.

A rough determination of the reaction enthalpy change between 23°C and 60°C yielded a ΔH° of 15 ± 4 Kcal/mole. The ΔH° was obtained by measuring the effects of heat on the equilibrium phosphorus distribution between solution and alumina. Generally speaking, chemical reactions range upward from 20 Kcal/mole, while ion-exchange reactions usually vary from 2 to 10 Kcal/mole. It may be concluded that phosphorus adsorption on alumina represents a dual-type ion exchange and chemical reaction. The fact that ion exchange was taking place was established by preparing the hydroxide form of alumina and displacing with 0.1 *M* Na_2HPO_4. Neufeld and Thodos (19) obtained the same results with a nitrate form alumina.

Secondary Adsorption

As reported earlier in this paper, polyvalent anions such as phosphorus are involved in secondary adsorption reactions as well. Small alumina columns with various phosphorus concentrations in the standard influent were compared on the basis of phosphorus removal. At 10 percent breakthrough, the throughputs for 10.3, 7.0, and 3.5 mg P/l in the standard influent were 900, 1,400, and 1,900 column volumes, respectively. About the same loading differences were maintained between

the isotherms for other breakthrough values. If the relationship between phosphorus removal and alumina surface area were a simple one, halving the phosphorus concentration without changing the surface area should give twice the influent throughput volume to the same percent breakthrough. Since the relationship between alumina surface area and phosphorus removal obviously is not a simple inverse one, other factors, such as the formation of complexes with other ions contained in the solution, must be considered. The divalent cations of calcium and magnesium would be most apt to enter into complex formation with phosphorus. The effect on phosphorus removal of deleting Mg^{+2} (25 mg/l) and Ca^{+2} (60 mg/l) from the standard influent was measured. Phosphorus was removed from the influent containing no calcium or magnesium, but the phosphorus loading was about halved when compared to a standard influent containing the usual calcium and magnesium concentrations. Most of the original phosphorus capacity was restored by 25 mg/l of Mg^{+2}. At least part of the phosphorus was bonded onto the alumina surface by a complex involving Mg^{+2} and Ca^{+2}. As the phosphorus concentration increases, the portion of the phosphorus removed by this complex may increase, giving larger phosphorus-removal values than could be expected from a consideration of alumina surface area alone.

Interference

The competition or effects of other anions on phosphorus removal was of interest because large concentrations of other anions could significantly lower the phosphorus capacity of the alumina. Sulfate ion was chosen to demonstrate phosphorus-capacity effects due to similarities in the behavior of SO_4^{-2} and HPO_4^{-2}. A sulfate ion concentration greater than 5×10 *M* is necessary to affect the phosphorus removal adversely from standard SSE by the boehmite. This conclusion is probably valid for other anions with the exception of arsenate. $HAsO_4^{-2}$ could be expected to substitute for HPO_4^{-2} in the adsorption reaction with little difference in alumina selectivity between the two anions.

Grain Size

Though the aluminas used in the study were all high in surface area, grain size still had an effect on the efficiency of phosphorus removal.

Assuming a normal distribution within ize ranges and a spherical shape, the 10- to 20-mesh range should have an external surface area of less than 1 sq m/g and the 48- to 100-mesh somewhat larger. A B.E.T. surface area, however, is 290 sq m/g for both size ranges of alumina gel. The same high surface area is available for all gel size ranges, and all sizes would remove the same amount of phosphorus if equilibrium between phosphorus and solution were attained. The effects of size range on phosphorus loading characteristics seen in Figure 2 are due to the kinetics of phosphorus diffusion from the solution surrounding the alumina particle, through the particle to the adsorption site.

Diffusion kinetics (20) for exchange reactions are of two types, particle diffusion and film diffusion. Particle diffusion is so called because diffusion of the exchanging ions from alumina particle surface into the particle is the rate-determining step. Particle diffusion assumes a high concentration of the exchanging ions in the solution surrounding the alumina particle. If the size of the exchanging ions is very large, however, the concentration of ions in the solution can be quite low and still exhibit particle diffusion. Film diffusion is so named because diffusion of the exchanging ions within the particle is very fast, leading to depletion of these ions in a film of solution surrounding the alumina particle. Diffusion of ions across the film surrounding the particle is the rate-determining step. The concentration of ex-

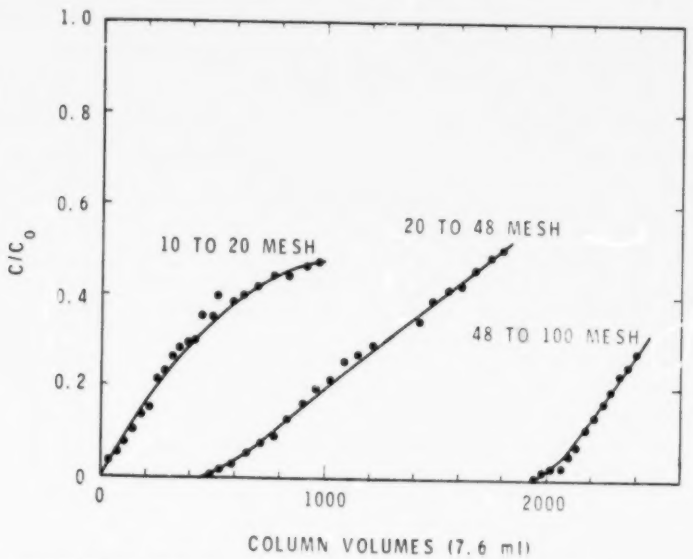

FIGURE 2.—Effect of grain size range on phosphorus adsorption kinetics. Sieve dimensions are U. S. Standard Series. Column material: alumina gel, mesh sizes as indicated; surface area: 290 sq m/g; flow rate: 35 column volumes/hr; temperature: 23°C; influent: SSE with 6.7 mg P/l.

changing ions in the solution is usually low. The diffusion time necessary to attain a given fraction of equilibrium loading varies inversely as the square of the particle radius in the case of particle diffusion, and by a simple inverse ratio to particle radius in the case of film diffusion. From a consideration of the curves shown in Figure 2, one can see that particle diffusion probably is rate-controlling, despite the low concentration of phosphorus. However, more elaborate techniques are required to verify the rate-controlling step.

Elution

Elution of SSE phosphorus-loaded columns with acidic solutions and sodium sulfate of various strengths were disappointing. Elution rates fell off rapidly and were generally inefficiently slow. In addition, acidic elutions left the column in a condition that was detrimental to phosphorus reloading. A 1 *N* H_2SO_4 alumina column prewash resulted in a 2 to 5 percent phosphorus leakage and reduced phosphorus loading by about 40 percent.

Basic elutions are recommended because they are more efficient and do not reduce the following phosphorus reloading. Sodium hydroxide and sodium carbonate phosphorus elution curves are given in Figure 3. The sodium carbonate elution rate was slower than that of sodium hydroxide. Both curves of Figure 4 represent elution of a first cycle loading alumina column, and illustrate that diffusion of hydroxide ion into the alumina particle and of phosphorus out of the particle requires considerable time. More time was required to regenerate the last 20 percent of the alumina's phosphorus capacity than the duration of the elution afforded.

A leaching experiment with 1 *M* NaOH and boehmite and alumina gel was conducted to obtain a feeling for alumina losses during sodium hydroxide elutions. Losses would occur

mainly during elution because alumina solubility in solutions such as SSE is very low. Moreover, excessive losses of alumina during elution would adversely affect wastewater treatment costs. Eight-gram columns of 16- to 60-mesh alumina gel and 100- to 200-mesh boehmite were leached for several days at a flow rate of 30 column volumes/hr with 1 *M* NaOH. The dissolution rate of alumina gel was 6.3 wt percent/24 hr and for boehmite, 1.2 wt percent/24 hr. Another commercially available alumina gel lost 7.0 wt percent/24 hr. The above weight losses may be compared to Yee's reported losses of 8 percent per elution for boehmite and up to three or four times the 8 percent loss for alumina glass. Although the weight loss ratio is the same as that of this study, the lower losses here probably reflect leaving out the acid step in regeneration.

If sodium hydroxide is to be used as an alumina column regenerant, some method of disposal or reuse must be found for the spent regenerant solution. Lime represented a possible economical solution to the problem by removing phosphorus and carbonate from the spent regenerant sodium hydroxide and allowing NaOH reuse. The phosphorus was precipitated as a hydroxyapatite, and carbonate, originally HCO_3^- before elution, also was removed as $CaCO_3$. Both constituents were identified by X-ray diffraction of the solids. An apatite is the raw natural material used in making fertilizer and phosphorus chemicals. The monetary value of the apatite produced would probably be very small.

Fouling

Some alumina column fouling with calcite ($CaCO_3$) occurred during loading with high-pH synthetic secondary wastewater effluents. An alumina sample removed from the column for X-ray diffraction study showed the presence of calcite coating the alumina grains. This precipitation of calcite on the alumina lowers the alumina surface area available for phosphorus adsorption, and calcite is not removed from the column during elution with

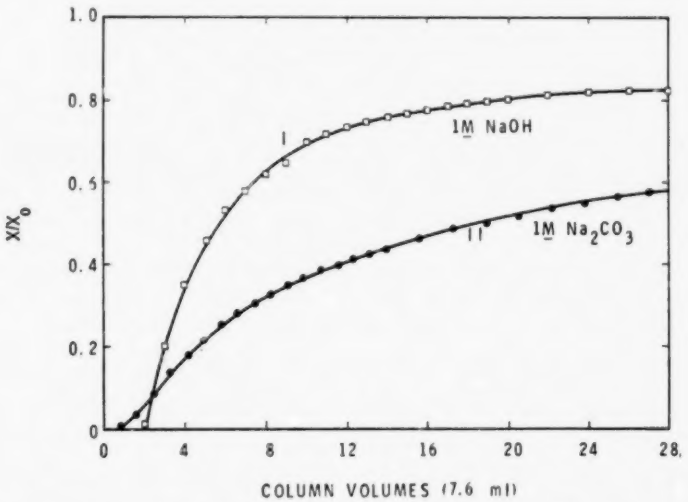

FIGURE 3.—Sodium carbonate and sodium hydroxide phosphorus elution curves. X/X_o is the fraction of P removed from the column by the elution treatment. Column material: boehmite, 100 to 200 mesh, 200 sq m/g; flow rate: 30 column volumes/hr; elution solutions: I—1 *M* NaOH, $X_o = 74.6$ mg P, II—1 *M* Na_2CO_3, $X_o = 54.7$ mg P.

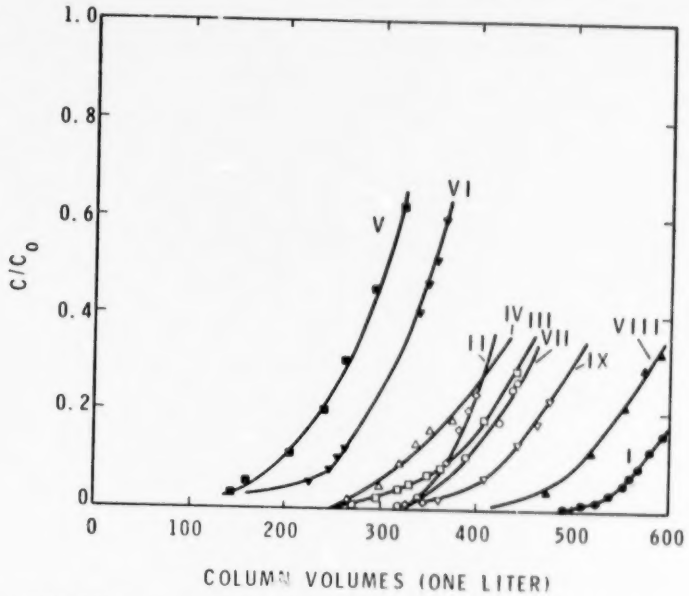

FIGURE 4.—Comparison of consecutive phosphorus loading curves for a variously regenerated 2-in. (5.1-cm) alumina column. Column material: alumina, 20 to 48 mesh; influent: Richland secondary effluent (10.3 mg P/l); flow rates: Cycles I, II, and III—15 column volumes/hr, Cycles IV through IX—5 column volumes/hr; temperature: 23°C; elution treatment: I—10 1 1 *M* NaOH, II—10 1 1 *M* NaOH, III—50 1 sat. $Ca(OH)_2$ solution, IV—50 1 sat. $Ca(OH)_2$ solution, V—15 1 10 percent HCl, VI—12 1 2 *M* NaOH, VII—16 1 2 *M* NaOH, VIII—8 1 2 *M* NaOH. Elution treatments followed above-associated loading cycle numbers.

sodium hydroxide. As alumina grains became calcite-coated, phosphorus surface adsorption was effectively blocked. Several ways are available to treat the calcite problem. One way is to leach the column with a bicarbonate solution. Nearly all of the phosphorus capacity was regained after $NaHCO_3$ solution was recirculated through the column. Lime can be added to the phosphorus-containing $NaHCO_3$ solution to precipitate apatite, if an excess of lime is avoided. The $NaHCO_3$ solution can then be reused. It is still necessary to remove any alumina-adsorbed phosphorus with NaOH. The problem of calcite imbalance was not encountered with actual secondary wastewater effluent from the Richland trickling filter plant.

Limitations of SSE

If Richland effluent is used to load both the large (1-l) and small (6.7-ml) columns, the resulting phosphorus breakthrough curves are very similar. However, if the Richland effluent breakthrough curve is compared to the phosphorus breakthrough curve of the SSE on the same size column, the results are considerably different. The SSE cannot really represent a synthetic secondary wastewater effluent, at least in terms of total alumina phosphorus capacity. Even though the phosphorus capacity of the alumina is reduced when Richland effluent is used for loading, the characteristic reactions of alumina are the same in each case. The small column-SSE work is therefore useful in predicting how the alu-

TABLE II.—Richland Secondary Effluent Composition

Constituent	Concentration Range (mg/l)
Na^+	40–60
K^+	12–15
NH_4^+	10–14
Mg^{++}	6–9
Ca^{++}	25–40
NO_3^-	11
P	8–12
Alkalinity as $CaCO_3$ equivalent	180–190
pH	7.2–7.8

mina will react to given loading and elution conditions. The small column-SSE work is not useful for predicting phosphorus capacities of alumina when actual wastewater effluents are used for loading.

One-Liter Alumina Columns

The composition of Richland trickling filter effluent used as the influent in the 1-l column studies varied over the range given in Table II. Total phosphorus analyses showed that more than 95 percent was present as orthophosphate, not an unusual result for secondary effluents (18). One-liter alumina columns (5.1 cm diam by 49 cm high) were used with Richland effluent to determine the effects of the elution method on subsequent phosphorus reloading. The Richland wastewater effluent was stored outside in a covered 500-gal (1,890-l) polyethylene tank. The effluent was pumped inside, degassed by heating to room temperature, and passed through a 7.6-cm-diam by 60-cm granulated charcoal column before going to the alumina.

Effects of Elution Agents

The 1-l alumina column loading data are given in Figure 4. Note that there is an initial drop in capacity going from cycle I to cycle II, as there was when SSE was used as an influent. Various elution treatments were tried after each cycle to ascertain the effects, if any, on the following loading cycle. Ten column volumes of 1 *M* NaOH were used to elute the column after loading cycles I and II. Saturated $Ca(OH)_2$ solution was tried as an eluting agent following loading cycles III and IV. The phosphorus capacity fell steadily for the following loading cycles IV and V. Precipitation of solids in the alumina bed was observed. Recovery and X-ray diffraction of a sample of the solids showed that they were mostly calcite and a little apatite. A gram of the precipitated solid contained 23 mg of phosphorus. As the alkalinity of the Richland effluent implies, it must contain about 115 mg HCO_3^-/l. Since the alumina can adsorb part of this HCO_3^-, as well as the phosphorus, the $Ca(OH)_2$ solution must immediately precipitate calcite (and apatite) within the column and on the alumina grains and lead to reduced phosphorus-adsorption capacity.

An acid wash after cycle V contained 8.4 g of phosphorus in 15 l. The following loading, cycle VI, showed low capacity because acid is a poor phosphorus-eluting agent and acid treatment of alumina, as shown by previous work, results in lowered phosphorus capacity. A regeneration with 1 *M* NaOH following loading cycle VI resulted in restoration of the column to normal phosphorus operating capacity (400 column volumes of Richland effluent to 10 percent breakthrough). Nearly twice as much phosphorus was eluted after loading cycle VI as was loaded on the column by cycle VI. The extra phosphorus was left over from an incomplete elution with HCl after loading cycle V. Nearly all of the phosphorus loaded during cycle VII was removed by the 1 *M* NaOH elution followed cycle VII.

Elution of cycle VIII loading was accomplished with eight column volumes of 1 *M* NaOH. The column was drained before elution to avoid contamination of the NaOH by Richland effluent, and drained after elution to

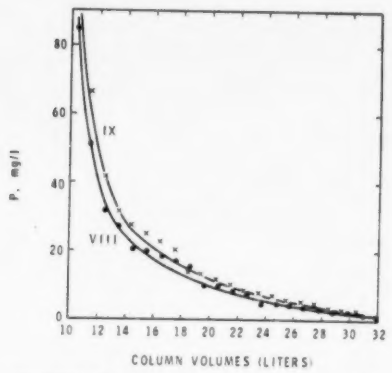

FIGURE 5.—Phosphorus concentrations in the column wash water following elution of VIII and IX. Column, flow rate, and temperature are the same as those given in Figure 4.

cut NaOH losses. The column then was washed with tap water. The phosphorus content of the wash water is given in Figure 5. This water could be sent to the plant head end to avoid phosphorus contamination of the product water.

The high-phosphorus wash water through 20 column volumes varies over the range 10 to 83 mg P/l. The rest of the wash ranges between 1.2 and 10 mg P/l and is relatively low in pH.

Removal of Biodegradable Materials

For the first eight phosphorus-loading cycles on the 1-l column, charcoal-filtered Richland effluent was used as the influent to reduce the applied biodegradable materials that might interfere with phosphorus removal.

The charcoal column was 7.6 cm in diameter by 75 cm in height, and was replaced on the ninth loading cycle by a 20- to 50-mesh sand filter 7.6 cm in diameter by 20 cm in height. The resulting phosphorus loading-curve is given in Figure 4. The alumina and the influent solution were somewhat more colored than with the charcoal filtration, but the loading cycle was otherwise normal. Carbon treatment is probably not justifiable if phosphorus removal is the only goal.

The NaOH solutions, after use, contained the color units shown in Table III. The colors matched fairly well when determined by the standard platinum-cobalt method.

Stirring the used NaOH with 10 to 20 g of $Ca(OH)_2$ resulted in removal of most of the color and phosphorus (and also CO_3^{-2}) from the solution. The resulting solids settled well and the NaOH could be reused.

Phosphate Removal with Lime

An actual 2 *M* NaOH used eluting solution was used to obtain phosphorus removal data with lime under equilibrium conditions, as shown in Figure 6. The hydroxyapatite theoretical removal curve is included for comparative purposes. If all of the added lime were used in the precipitation of $Ca_5(PO_4)_3OH$, the dashed line of Figure 6 would result. The lower portion of the curve is below the actual phosphorus removal, indicating that a more phosphorus-rich compound than the above is formed with the added calcium in this portion of the curve. In the upper portion of the curve, actual phosphorus removal is less than that of hydroxyapatite, probably because of removal of carbonate as $CaCO_3$.

Costs

If 2.0 g/l of $Ca(OH)_2$ were added to the 8 l of NaOH eluting solution, representing the phosphorus removal from about 400 l of secondary effluent, lime costs at 1¢/lb (2.2¢/kg) would

TABLE III.—Color Test Results on 2 *M* NaOH Elution Following Loading Cycle VIII

Cumulative Column Volumes	Color Units
2	5
3	125
4	175
5	45
6	35
7	25
8	15
9	5

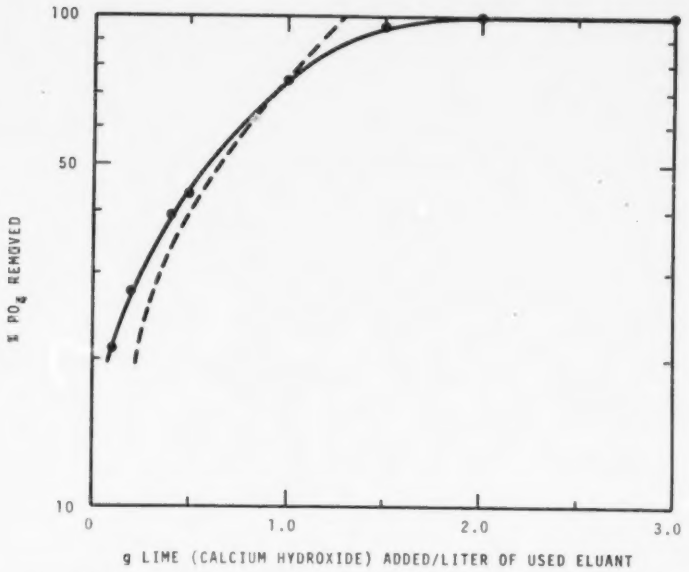

FIGURE 6.—Equilibrium distribution of phosphorus between an eluting solution, generated after loading an alumina column with phosphorus from Richland secondary effluent, and added increments of lime. Used 2 *M* NaOH eluting solution contained 1.850 g PO_4/l plus other anions including CO_3^{-2}. The dashed line represents the theoretical stoichiometric utilization of the added $Ca(OH)_2$ in the formation of $Ca_5(PO_4)_3OH$, or hydroxyapatite.

amount to about 0.33¢/1,000 gal (0.09¢/cu m) of treated secondary effluent. Alumina dissolution losses of about 0.33 wt percent/hr occurred with 1.0 *M* NaOH, or about 1.2¢/1,000 gal (0.3¢/cu m) of treated secondary effluent if the 1-l column were used for phosphorus removal. Estimated treatment cost of secondary effluent is given in Table IV. Based on present information, removal of phosphorus on alumina columns as a tertiary treatment process will cost from 5 to 6¢/1,000 gal (1.3 to 1.6¢/cu m), which includes the cost of pretreatment by filtration.

TABLE IV.—Estimated Operating Costs for a 10-Mgd (37,850-Cu m/day) Plant

Item	Cost (¢/1,000 gal)
Power, labor, maintenance, and capital amortization	2.50
Filtration	1.50
Lime	0.33
Caustic makeup	0.30
Alumina makeup	1.20
Total	5.83

Note: ¢/1,000 gal ÷ 3.785 = ¢/cu m.

Conclusions

The effects of various compositional changes on phosphorus removal by alumina columns from a synthetic secondary wastewater effluent were studied.

1. The concentration of Mg^{+2} and Ca^{+2} showed marked effects on alumina column phosphorus capacity, with the phosphorus capacity about half for the solution containing no Ca^{+2} or Mg^{+2} as compared to solutions containing Ca^{+2} and Mg^{+2}. Adsorption onto the alumina occurs partly as a calcium- or magnesium-phosphorus complex rather than as a simple phosphorus anion.

2. Increasing the competing sulfate concentration in the influent solution

to 4,800 mg SO_4^{-2}/l showed little effect on phosphorus adsorption by alumina.

3. Raising the pH of the synthetic wastewater effluent to greater than 8.0 led to precipitation of calcium carbonate on the alumina grains, which progressively lowered alumina phosphorus capacity. This problem was not encountered when actual wastewater effluent was used.

4. Alumina columns could be regenerated satisfactorily with NaOH alone in about 1 hr. An acidic wash was not required. Alumina dissolution in a 1 *M* NaOH eluting solution averaged 0.33 wt percent/hr.

5. Wastewater effluent from the Richland trickling filter plant was used in scale-up to 1 l alumina columns. Approximately 400 column volumes of Richland effluent were required to reach 10 percent phosphorus breakthrough. If two columns were operated in series, more than 600 column volumes could be loaded on the first column before elution would be required.

6. Elution of phosphorus was accomplished with 8 column volumes of 1 *M* NaOH, followed by 20 column volumes of wash water. The column was then ready for reloading with phosphorus. If the column is drained at the end of the elution step, NaOH losses are about 5 percent of a column volume per elution. The wash water containing phosphorus and NaOH washings can be recycled back to the head end of the treatment plant. The eight-plus column volumes of NaOH contaminated with HCO_3^- and phosphorus, as well as organic coloring matter, can be cleaned at a lime cost of about 0.33¢/1,000 gal (0.09¢/cu m) of treated secondary effluent. The phosphorus is removed as $Ca_5(PO_4)OH$ (hydroxyapatite) and the HCO_3^- as $CaCO_3$ (calcite). Most of the coloring matter settles out with the above solids, allowing reuse of the NaOH. Thus, only a small volume of solid waste is produced by the phosphorus-removal process.

7. Estimated treatment cost, including filtration, for a 10-mgd (37,850-cu m/day) plant is between 5 and 6¢/1,000 gal (1.3 and 1.6¢/cu m) for secondary effluent containing 10 to 12 mg P/l.

Acknowledgment

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